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## Far Ultraviolet Absolute Flux of $\alpha$ Virginis<sup>1</sup>

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### ABSTRACT

We present the far ultraviolet spectrum of  $\alpha$  Virginis taken with EURD spectrograph on-board MINISAT-01. The spectral range covered is from  $\sim 900$  to  $1080 \text{ \AA}$  with  $5 \text{ \AA}$  spectral resolution. We have fitted Kurucz models to IUE spectra of  $\alpha$  Vir and compared the extension of the model to our wavelengths with EURD data. This comparison shows that EURD fluxes are consistent with the prediction of the model within  $\sim 20 - 30 \%$ , depending on the reddening assumed. EURD fluxes are consistent with Voyager observations but are  $\sim 60\%$  higher than most previous rocket observations of  $\alpha$  Vir.

*Subject headings:* stars: early-type — stars: individual ( $\alpha$  Vir) — ultraviolet: stars

### 1. Introduction

Observations of OB stars in the far-ultraviolet (FUV), below  $1100 \text{ \AA}$ , are important to address several issues, such as the interaction of these stars with their surrounding ISM, or

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<sup>1</sup>Based on the development and utilization of the Espectrógrafo Ultravioleta de Radiación Difusa, a collaboration of the Spanish Instituto Nacional de Técnica Aeroespacial and the Center for EUV Astrophysics, University of California, Berkeley

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the determination of interstellar dust size. These observations can also serve as a test of stellar atmosphere models and to set spectrophotometric standards in the FUV, which are brighter and more abundant than white dwarfs, for future space observatories.

There are very few FUV spectroscopic observations of stars. Since the first rocket observations of stellar emission in the FUV (Brune, Mount, & Feldman 1979), several attempts have been made to determine the spectral energy distribution of stars of different spectral types in this wavelength range. In early work rockets were used to study stars in the FUV, and there were some spacecraft observations by Voyager (Broadfoot et al. 1977) and Copernicus (Rogerson et al. 1973) spacecraft observations. More recently, three instruments with FUV spectrometers, HUT (Davidsen 1990), ORFEUS (Hurwitz & Bowyer 1991) and UVSTAR (Stalio et al. 1993), have flown on-board the Space Shuttle.

Absolute calibration in this wavelength range is difficult due to the absence of primary or secondary standards, and indirect calibrations were applied in all cases. The consequence is that large flux differences, of up to a factor of ten at certain wavelengths, are found between observations of the same star taken with different instruments, and none of them agrees with Kurucz model atmospheres below 1000 Å. Voyager (Chávez, Stalio, & Holberg 1995) and HUT (Buss, Kruk, & Ferguson 1995) observations report fluxes higher than the model predictions below 1200 Å. On the other hand, rocket observations (Brune et al. 1979; Carruthers, Heckathorn, & Opal 1981; Woods, Feldman, & Bruner 1985; Cook, Cash, & Snow 1989) gave substantially lower fluxes than those from Voyager, and also lower than the fluxes predicted by Kurucz model atmospheres.

$\alpha$  Vir is one of the most studied stars in the FUV. It has been observed by Copernicus (York & Kinahan 1979), Voyager 1 and 2 (Holberg et al. 1982), and by rockets (Brune et al. 1979; Cook et al. 1989, and Wilkinson et al. 1995).

The fundamental parameters of  $\alpha$  Vir are well known. Spica is a double-lined spectroscopic binary with an ellipsoidal variation of 0.03 mag. due to tidal distortion with 4-day orbital period, superposed to  $\beta$  Cephei-type pulsations of the primary, of 0.016 mag. amplitude and a period of 0<sup>d</sup>.1738 (Shobbrook et al. 1969).

The radius of the primary, determined interferometrically by Herbison-Evans et al. (1971), is  $R_1 = 8.1 \pm 0.5 R_\odot$  for a distance of  $84 \pm 4$  pc, and its spectral type is B1V. The secondary component of  $\alpha$  Vir is probably a B4V star, for which Popper (1980) assumed a  $(B - V) = -0.18$ , leading to a radius of  $R_2 = 4.16 \pm 1.17 R_\odot$  which is consistent with the mass ( $10.9 \pm 0.9 M_\odot$ ) deduced by Herbison-Evans et al. (1971). Its parallax has been measured by Hipparcos ( $12.44 \pm 0.86$  mas, Perryman et al. 1997). Corrections for the radii of the component stars of  $\alpha$  Vir due to this new value of the distance lead to  $R_1=7.78$  and

$R_2=3.99$ .

Integrated photometry for the two components from the literature as extracted from the SIMBAD database indicate  $V = 0.98$ ,  $B - V = -0.235$ , and  $U - B = -0.94$  for Johnson photometry and  $b - y = -0.114$ ,  $m_1 = 0.080$ , and  $c_1 = 0.018$  for Stromgren uvby photometry. Crawford  $H\beta$  photometry gives  $\beta = 2.607$ .

In this paper we present the spectrum of  $\alpha$  Vir obtained with EURD (Espectrógrafo Ultravioleta extremo para la Radiación Difusa) on-board MINISAT-01. We compare our observations with previous ones and with Kurucz models (ATLAS9, Kurucz 1993). Our observations allowed us to obtain a flux calibrated spectrum of  $\alpha$  Vir with the best signal-to-noise ratio and spectral resolution to date in the FUV range.

With this observations we intend to determine the absolute flux of  $\alpha$  Vir in the FUV, for which discrepancies have been found in previous works.

## 2. Observations and data reduction

EURD was launched on April 1997 on-board the Spanish satellite MINISAT-01, which has a retrograde orbit of  $151^\circ$  inclination and an altitude of 600 km. Details on the mission can be found in Morales et al. (1998).

EURD is a spectrograph specially designed to observe diffuse radiation in the wavelength range from 350 to 1100 Å. It observes in the anti-sun direction and during orbital eclipse. A precise description of the instrument and its ground calibration can be found in Bowyer, Edelstein, & Lampton (1997). The detector is a photon counter device that produces spectral images, with spatial resolution capabilities along an axis perpendicular to the direction of spectral dispersion. The spectral resolution of the instrument is  $\sim 5$  Å. When a bright, early-type star falls within the  $\sim 25^\circ \times 8^\circ$  field of view, it shows up as emission longward of  $\sim 912$  Å, on a finite area along the spatial dimension. Given the mission pointing constraints, only stars within  $\sim 13^\circ$  from the ecliptic can be observed.

Observations of  $\alpha$  Vir presented in this paper were taken from 1998 April 13 to April 19, and 1999 April 2 to April 23. During the data reduction process, we tracked the position of the stellar emission on the detector for every second, extracted the photons detected within  $10'5$  from the emission maximum (to include all the stellar emission gathered during one second), and subtract a background from an area of the detector close to where the stellar emission lies. Photon counts are then corrected by the efficiency of the detector as

a function of incidence angle. The accumulated photon counts are converted to fluxes by applying the in-flight calibration performed with simultaneous observations of the full Moon with EUVE and EURD (Edelstein et al., in preparation).

### 3. Results and discussion

#### 3.1. The Far-UV spectrum of $\alpha$ Vir

Fig. 1 shows the spectrum of  $\alpha$  Vir, with a total integration time of  $1.06 \times 10^5$  s, and covering the wavelengths  $\lambda < 1080$  Å. The noise level of the spectrum is  $\sigma \simeq 3.3 \times 10^{-11}$  erg $^{-1}$  cm $^{-2}$  Å $^{-1}$  and the signal to noise ratio is  $> 3000$ . Some absorption features are obvious in the spectrum: the Lyman series of hydrogen at 937, 949, 972 and 1026 Å, N III at 989 Å, S III at 1012 Å, C II and O IV blended at 1037 Å, and an unidentified feature at  $\sim 1063$  Å (see York & Kinahan 1979).

#### 3.2. Comparison with model atmospheres

Atlas 9 Kurucz models properly reproduce the UV and optical spectra of B stars (Malagnini et al. 1985; Fitzpatrick & Massa 1998; Chávez et al. 1995). For wavelengths below 1200 Å, Holberg et al. (1982) reported for  $\alpha$  Vir a flux excess with respect to Kurucz models which is within the range of uncertainty of the reddening. They used a model atmosphere combination of 24500 K and 17000 K, and a reddening of  $E(B - V) = 0.02$ . In this wavelength range Buss et al. (1995) also found a flux excess of  $\sim 5\%$  at 1000 Å with respect to Kurucz models in their sample of galactic OB stars.

In this work, we first compared Kurucz models with IUE spectra of  $\alpha$  Vir and then we checked if the model extension to our wavelengths properly fits the EURD spectra. The FUV flux recorded by EURD is the combined flux of the two components of  $\alpha$  Vir binary system. Therefore it is necessary to build a combined Kurucz model corresponding to the  $\alpha$  Vir system. For this purpose we have adopted the effective temperatures given by Popper (1980),  $T_1 = 24500$  and  $T_2 = 17200$ . We computed the model used for the fit as a combination of Kurucz models of these temperatures (taking into account the radii of the two components), and gravity  $\log g = 3.69$ .

Spica IUE spectra (SWP33091HL and LWR13650HL) have been selected from the INES database. To create a single spectrum, we used the SWP spectrum shortward of 1940 Å, and the LWP one for longer wavelengths. The IUE data were degraded to the 10

Å spectral resolution of the models. Correction for interstellar HI and H<sub>2</sub> absorption are negligible, given the low hydrogen column density (Fruscione et al. 1994) in front of this relatively close star.

We normalized the resultant Kurucz model to the IUE spectrum. Adjusting to IUE observations we avoid the uncertainties possibly present in the determination of the angular radius. Fig. 2 shows the Kurucz model scaled to IUE, together with the EURD spectrum applying no reddening correction, binned down to match the spectral resolution of the models. The flux of the observed spectrum is  $\sim 20\%$  higher than the model flux. Fig. 3 shows the comparison of the Kurucz model with both EURD and IUE spectra.

We have also checked how a possible color excess could affect our results. The reddening correction is crucial at this wavelength range. Even though  $\alpha$  Vir has a very low optical reddening, at FUV wavelengths the extinction rises very steeply and must be corrected very carefully for an absolute flux determination. For wavelengths longer than 1200 Å the interstellar extinction has been well studied (Savage & Mathis 1979; Seaton 1979; Cardelli, Clayton and Mathis 1989; Fitzpatrick & Massa 1990). However, for wavelengths below 1200 Å, few attempts have been done to determine an extinction law (Longo et al. 1989; Snow, Allen, & Polidan 1990; Buss et al. 1994). The extinction laws obtained agree in shape with the extrapolation of Cardelli et al. (1989) law, but their absolute values are very dependent of the value of the ratio of total to selective extinction,  $R_v$ , in the star direction.

We have used the extrapolation of the average extinction law of Cardelli et al. (1989), applying  $R_v = 3.1$  for the diffuse interstellar medium, which is the average of the two more recent and accurate determinations of mean values of  $R_v$  (3.08, He et al. 1995; 3.12, Whittet & van Breda 1980). We have followed three different methods to obtain  $E(B - V)$ : column density of hydrogen, Strömgren uvby photometry, and Johnson UBV photometry. The highest value of color excess for  $\alpha$  Vir ( $E(B - V) = 0.02$ ) was obtained using Johnson UBV photometry and the intrinsic colors of Schmidt-Kaler (1982), taking the observed  $(B - V) = -0.235 \pm 0.08$  as derived from the recent ground UBV photometry carried out for the Hipparcos Mission (Perryman et al. 1997). This color excess of 0.02 is the same used by Holberg et al. (1982). Using this value to deredden IUE and EURD spectra, and scaling the corresponding Kurucz model to the new IUE flux, we find that EURD fluxes in this case would be in excess by 30% with respect to the model expectations. Since the flux excess using  $E(B - V) = 0$  was 20%, we can see that, in this case, the reddening correction is not critical in order to compare our results with the models.

We conclude that the data are reasonably consistent with Kurucz models both in flux and spectral shape. A fit to within 5%, would be obtained by increasing the adopted temperature of the primary by 600 K and assuming no reddening.

### 3.3. Comparison with previous observations

There have been very few observations of stellar spectra in the FUV. Among them,  $\alpha$  Vir is one of the most studied stars in this range (Brune et al. 1979; Holberg et al. 1982; Cook et al. 1989; Wilkinson et al. 1995). An indication of the difficulties involved in this study is that there exist significant differences in the flux derived for this star by different authors. Cook et al. (1989) and Brune et al. (1979) spectra are mutually consistent, but they are lower than those taken by Voyager (Holberg et al. 1982) and recently by Wilkinson et al. (1995) with a sounding rocket.

Fig. 4 shows the EURD spectrum compared with previous observations of  $\alpha$  Vir. The fluxes we derive are similar to those obtained by Holberg et al. (1982). By degrading our spectral resolution to match that of Holberg et al. (1982) observations, we see only a small discrepancy in the Lyman lines of hydrogen, whose absorption is deeper in the EURD spectrum. This can be due to residual atmospheric extinction in our data, which is not present in Voyager observations. Note, however, that the depth of the Lyman absorption lines in EURD data are more consistent with the prediction of the Kurucz models (Fig. 2).

As for the flux discrepancy between previous observations, we suggest that the fluxes obtained by EURD and Voyager better represent the real far-UV flux of  $\alpha$  Vir, while the group of observations that provide lower fluxes (Cook et al. 1989; Brune et al. 1979) seems to underestimate it. This suggestion is supported by the better consistency between our data and those of IUE, since the EURD spectrum is close to the Kurucz model that better reproduce IUE data (Fig. 2). The situation could switch in favor of the lower-flux observations if Kurucz models proved to overestimate the fluxes in this wavelength region.

## 4. Conclusions

We present new  $\alpha$  Vir observations below 1080 Å with improved spectral resolution and signal to noise ratio, taken with the EURD spectrograph on-board MINISAT 01. We compared the EURD  $\alpha$  Vir spectrum with a Kurucz model atmosphere computed with the best values of the temperature, distance and radius of the components of  $\alpha$  Vir binary system. This comparison shows that models are in reasonable agreement with the flux measured by EURD, being 20-30% higher than the models.

Our results support Voyager fluxes of Holberg et al. (1982), rather than the lower fluxes given by rocket observations.

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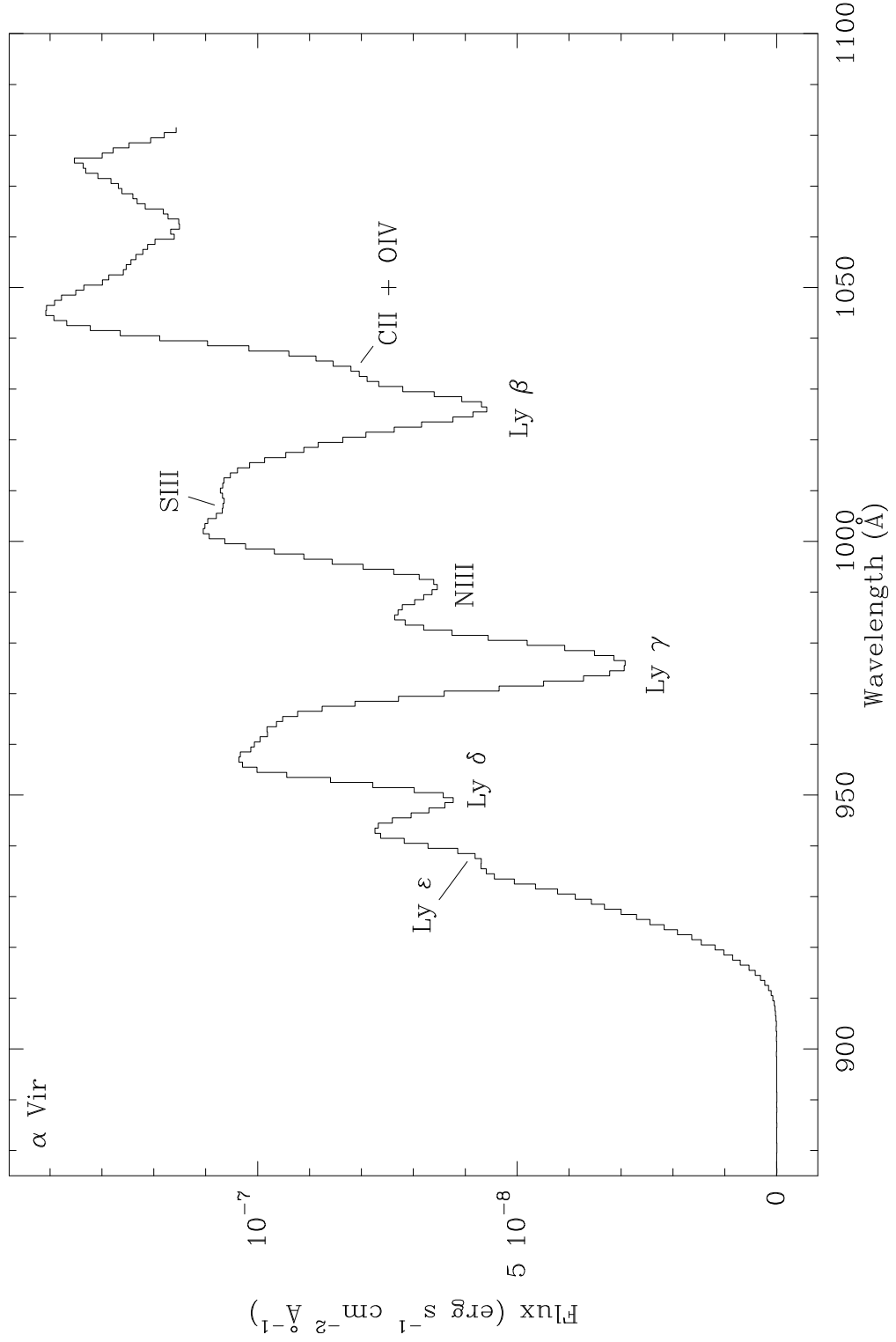


Fig. 1.— Spectrum of  $\alpha$  Vir as observed by EURD. Labels indicate the observed absorption features.

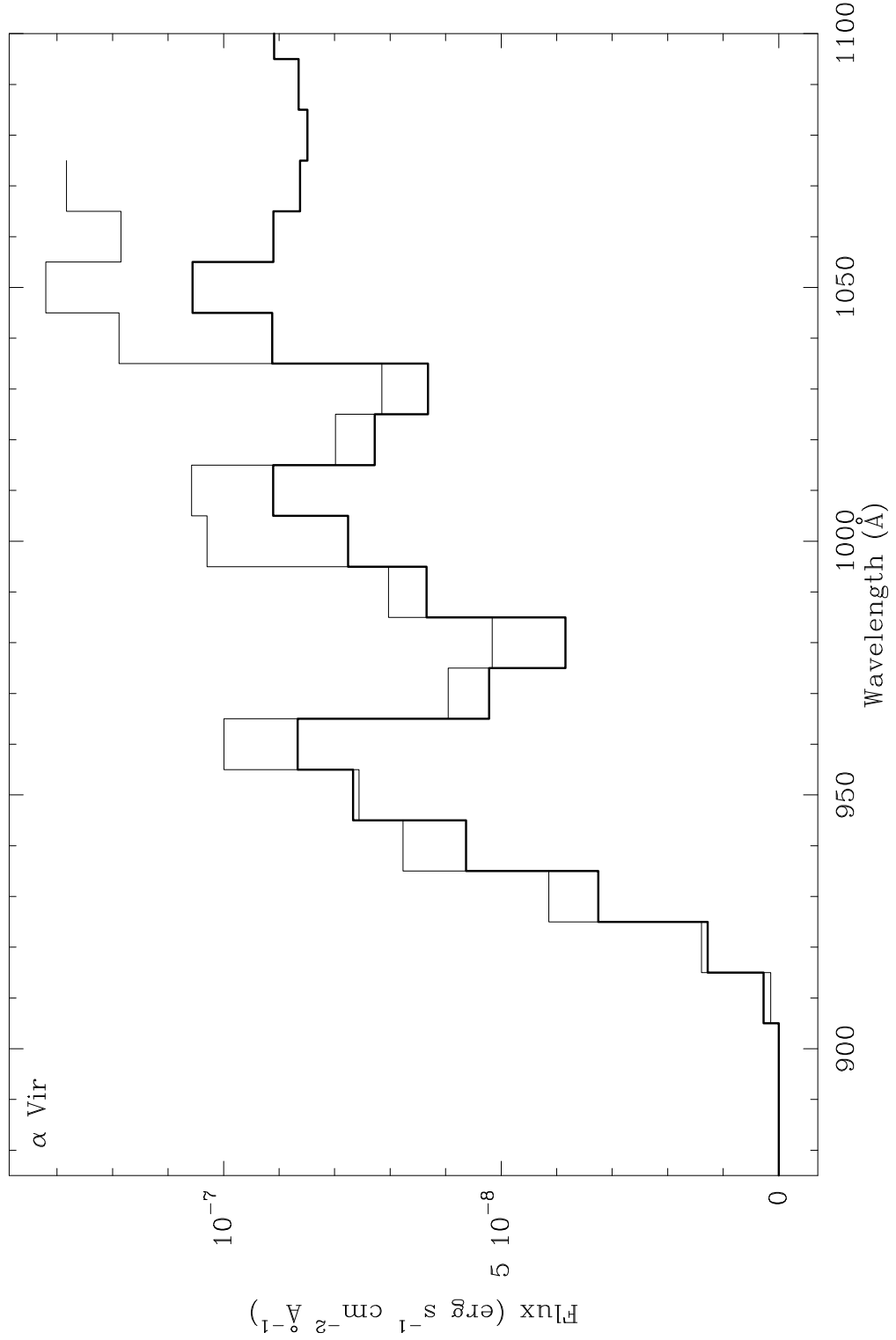


Fig. 2.— Spectrum of  $\alpha$  Vir observed by EURD, superposed on the corresponding Kurucz model (heavy line). The EURD spectrum has been binned down to match the spectral resolution of the model ( $10 \text{ \AA}$ ).

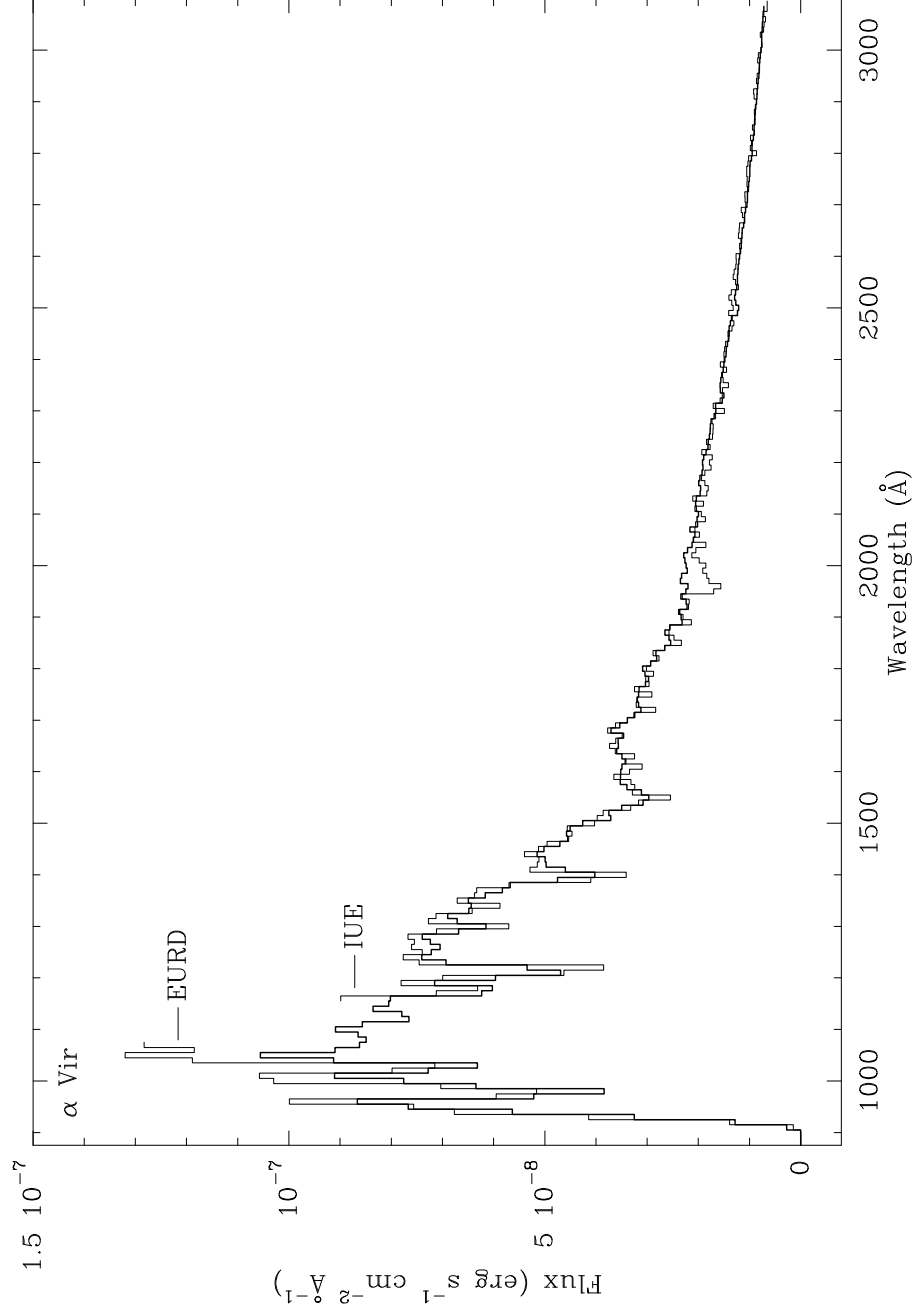


Fig. 3.— Spectra of  $\alpha$  Vir as observed by EURD ( $\lambda < 1070 \text{ \AA}$ ) and IUE ( $\lambda > 1160 \text{ \AA}$ ), superposed on the Kurucz model (heavy line) scaled to IUE data. Both EURD and IUE spectra have been binned down to match the spectral resolution of the model ( $10 \text{ \AA}$ ).

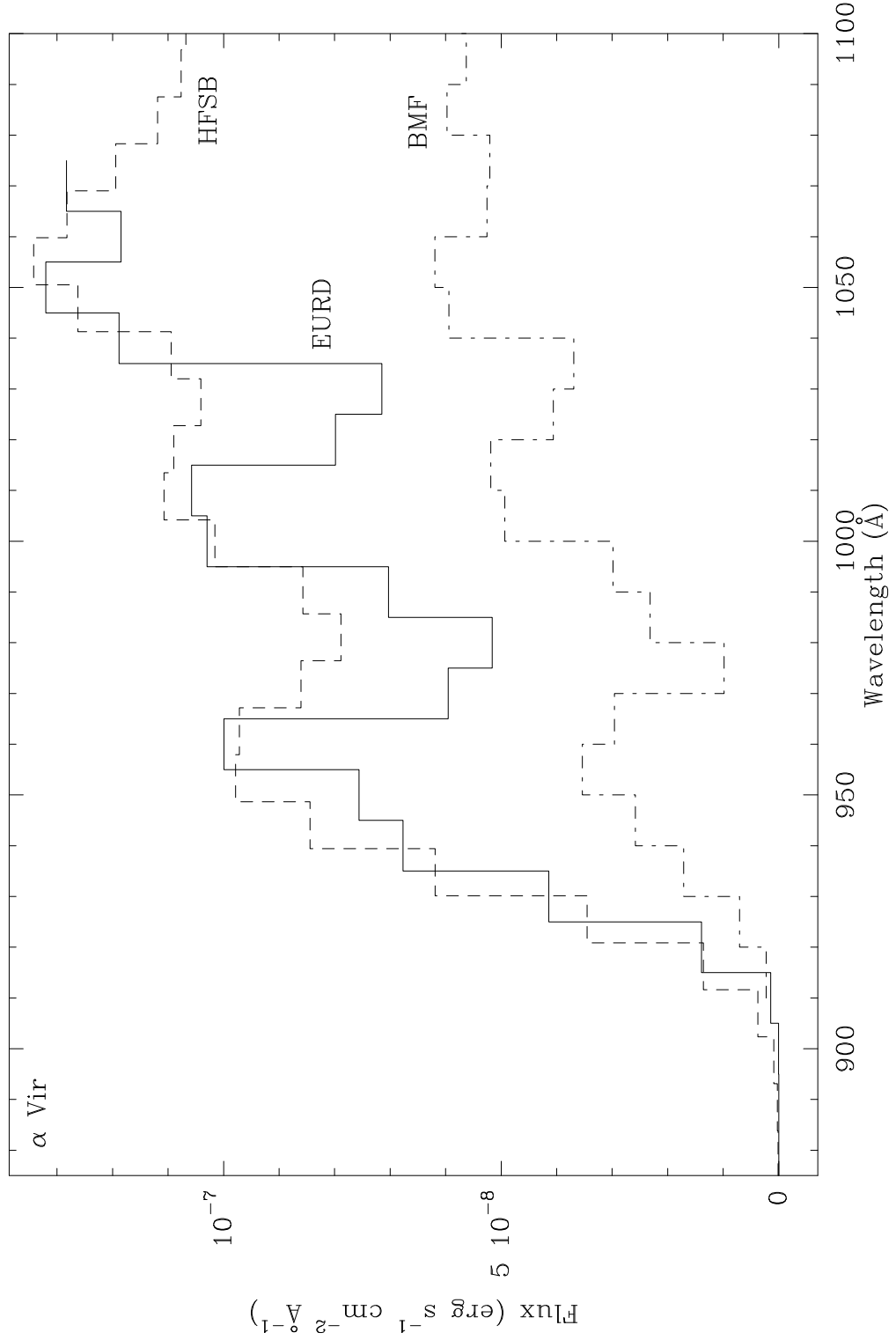


Fig. 4.— Spectrum of  $\alpha$  Vir observed by EURD (solid line), by Holberg et al. (1982) (HFSH, dashed line) and by Brune et al. (1979) (BMF, dashed-dotted line). The EURD spectrum has been binned down to a spectral resolution of  $10 \text{ \AA}$ .